Magnetic Reconnection at the Dayside Magnetopause

Paul Cassak
West Virginia University

SHIELDS Workshop: Shielding Society from Space Weather
April 5, 2016

Colleagues: ***Colin Komar***[1,2], ***Christopher Doss***[3], Rick Wilder[4], Stefan Eriksson[4], Jim Drake[5], Minna Palmroth[6], Sanni Hoilijoki[6,7], Yann Pfau-Kempf[6,7], Urs Ganse[7], John Dorelli[2], Brian Walsh[8]

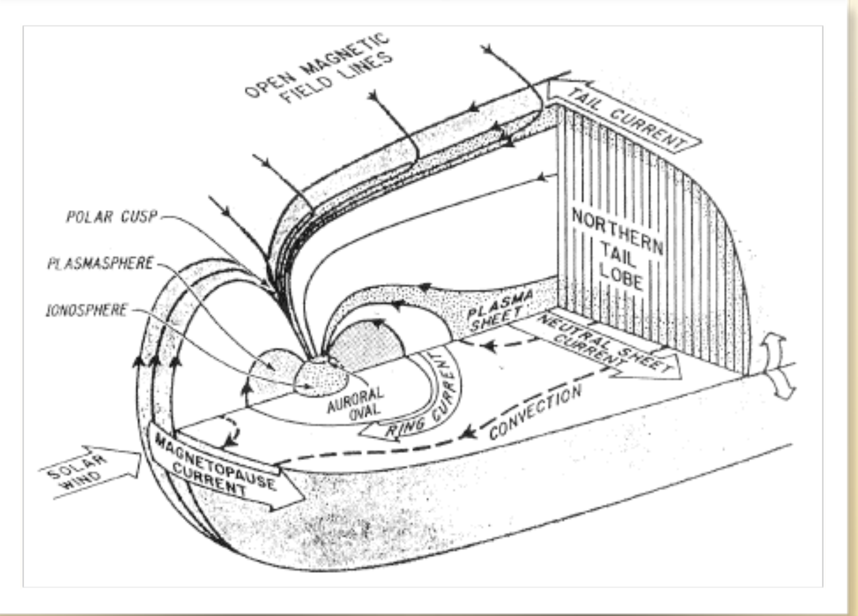
[1]CUA, [2]NASA-GSFC, [3]West Virginia University, [4]University of Colorado, Boulder (LASP), [5]University of Maryland [6]Finnish Meteorological Institute, [7]University of Helsinki, [8]Boston University

Supported by: NSF, NASA West Virginia Space Grant Consortium

Reconnection @ Dayside Magnetopause

- Allows the solar wind to couple to the magnetosphere
  - Crucial for space weather (e.g., Cassak, Space Weather, 2016)
    - Drives magnetospheric convection
    - Loads magnetotail with energy

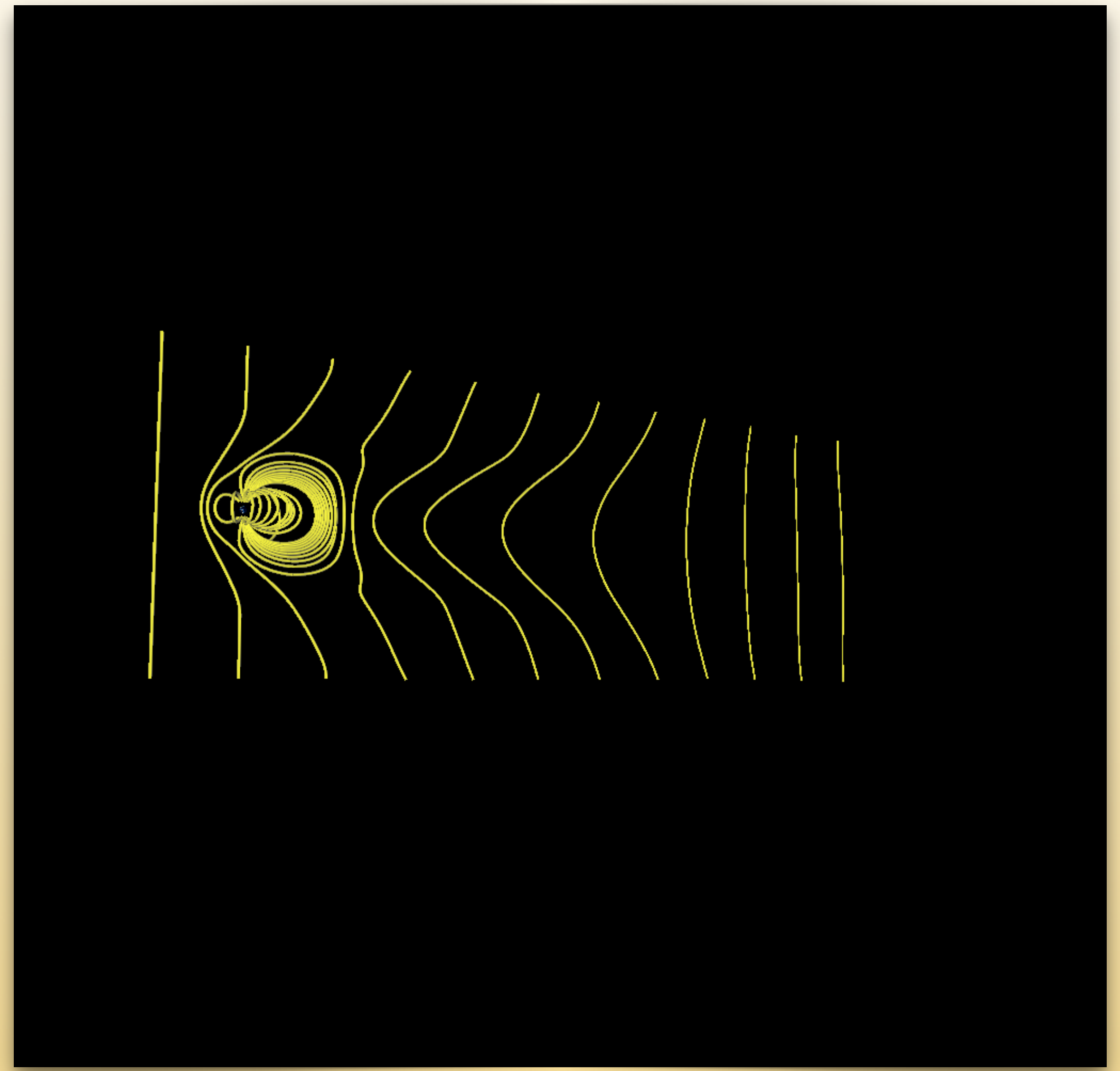
Developing a predictive capability for space weather requires an understanding of how reconnection participates in solar wind-magnetospheric coupling



After C. Russell

Reconnection @ Dayside Magnetopause

- Animation of solar wind-magnetospheric coupling
  - From global magnetospheric magnetohydrodynamic simulations using BATS-R-US code at NASA's CCMC
- Northward IMF
  - Reconnection occurs poleward of the cusps
    - Very weak coupling of solar wind energy to magnetosphere
- Southward IMF
  - Reconnection occurs in the subsolar region
    - Coupling of solar wind energy to magnetosphere is strong
      - Sets up Dungey cycle



Solar Wind-Magnetospheric Coupling

- Can think of solar wind-magnetospheric coupling as flow chart

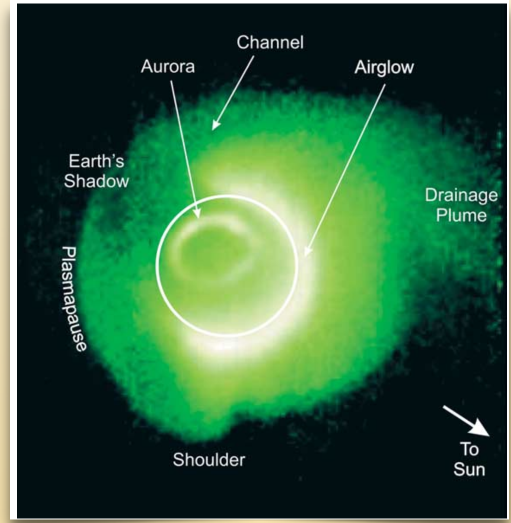
  - The black box is a nonlinear process
    - Likely also history dependent
      - The black box contains reconnection, large (MHD) scale processes, …

- Approaches to solve the problem
  - Empirical (e.g., Newell et al., 2007)
    - Use wealth of data to relate input to response
  - First-principles (e.g., Borovsky, 2008)
    - Understand the physics of the black box

Empirical approach has many merits and a long history;
this talk focuses on first-principles approach

First Principles

- The goal - predict magnetospheric response for given solar wind input
  - What does a prediction even look like?
    - Likely depends on what geomagnetic index is of interest
      - Undoubtedly, the rate that dayside reconnection proceeds is important
        - » Quantified by a global reconnection potential drop or a local reconnection electric field



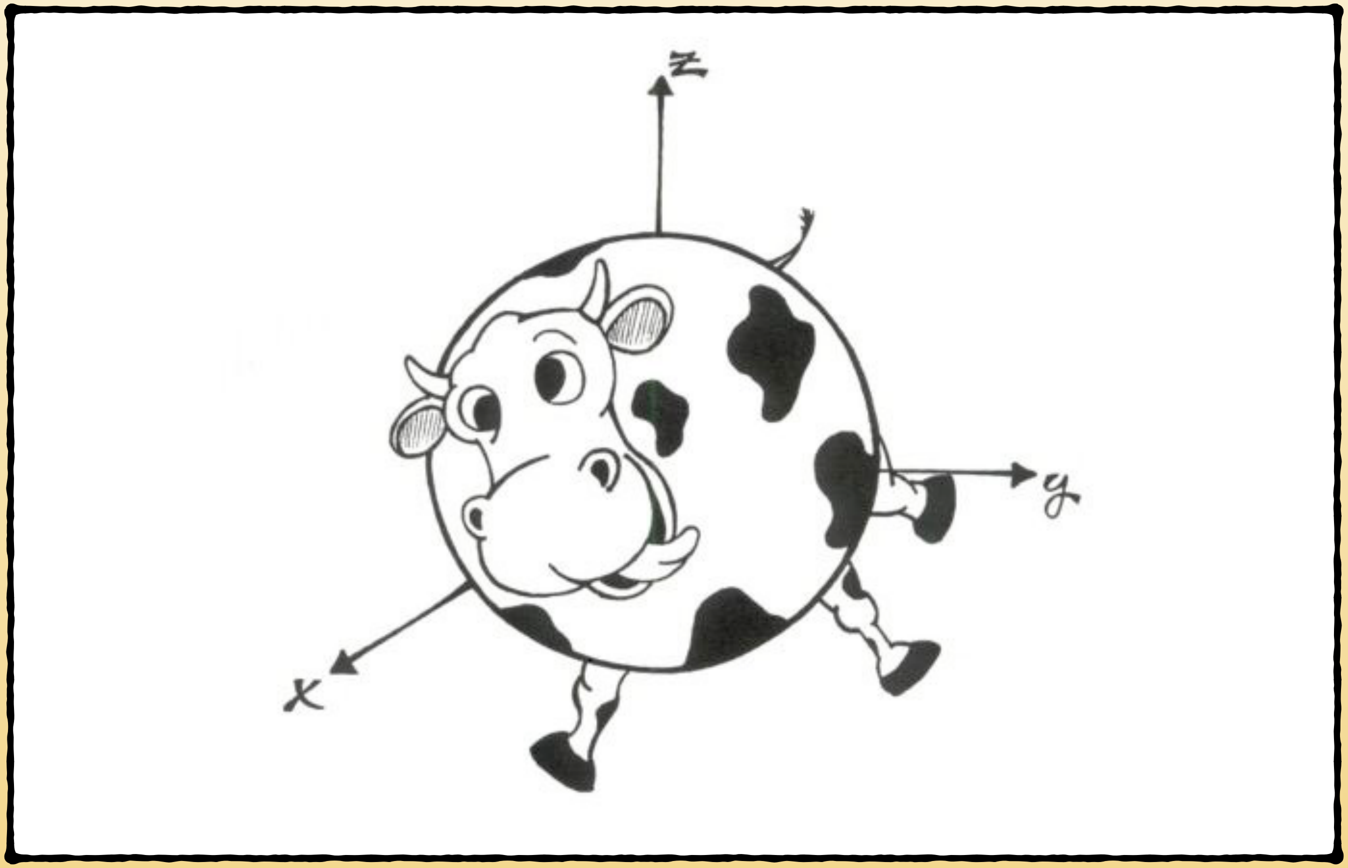
Sandel et al., 2003

- Very complicated!
  - Example - changes to the solar wind changes the size/shape of entire magnetosphere!
  - Must address the question of “global vs. local” control of reconnection
    - It was long thought that the amount and rate of flux reconnected at dayside is controlled (solely) by input from the solar wind (up to saturation of polar cap)
    - Borovsky and Denton, 2006 showed geomagnetic indices are altered when a plasmaspheric plume (pictured) reaches the dayside reconnection site
    - Mass loading the magnetosphere decreases coupling efficiency (Zhang et al., 2016)

- This talk
  - Efforts to predict local reconnection rate in idealized geometry for dayside magnetopause conditions
  - Efforts to determine whether these simplified models work at the 3D magnetopause
    - Theory, 2D local reconnection simulations with fluid and PIC models, 3D magnetospheric fluid simulations
    - May have impact on other magnetopause phenomena, including FTE motion

The Reconnection Rate

- The local reconnection rate in a collisionless plasma is known (but not understood)
  - E ~ 0.1 in normalized units, $E \sim 0.1 B_L c_{A,L}/c$ in dimensional (cgs) units
    - Assumptions - steady, two-dimensional, symmetric, anti-parallel, stationary plasma



The Dayside

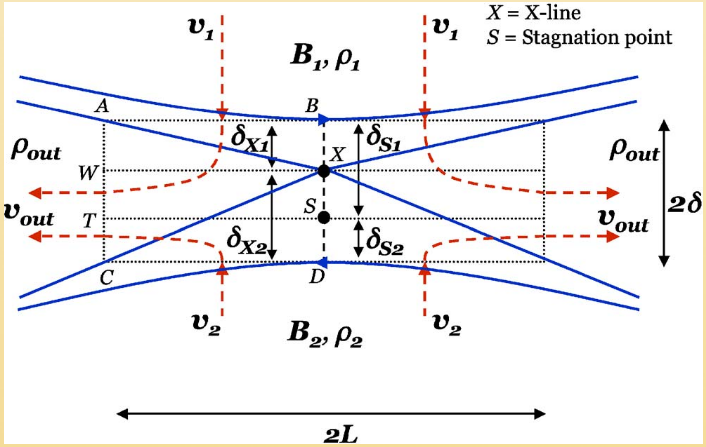
- Magnetopause conditions rarely satisfy these simplifying assumptions
  - Magnetosheath side has typical conditions of
    n_{sh} ~ 20 cm^{-3}, B_{sh} ~ 20 nT, $T_{i,sh}$ ~ 10s-100s eV, v_{sh} ~ 100 km/s
  - Magnetospheric side has typical conditions of
    n_{ms} ~ 0.1 cm^{-3}, B_{ms} ~ 56 nT, $T_{i,ms}$ ~ a few keV, v_{ms} ~ 0 km/s
    - Reconnection takes place at a locally asymmetric plasma, with one side potentially in motion

- How to generalize local reconnection rate prediction for such systems?
  - First consider asymmetry, but retain other assumptions
    - Can use conservation laws to predict reconnection rate (Cassak and Shay, 2007)

$$\boxed{E \sim 0.1 \left(\frac{2B_{L,1}B_{L,2}}{B_{L,1}+B_{L,2}} \right) \frac{c_{A,\text{asym}}}{c}}$$

$$c^2_{A,asym} \sim \frac{B_{L,1}B_{L,2}}{4\pi} \frac{B_{L,1}+B_{L,2}}{\rho_1 B_{L,2} + \rho_2 B_{L,1}}$$

  - Has been well-tested numerically in 2D systems with simple geometries



Cassak and Shay, 2007

Effect of Magnetosheath Flow?

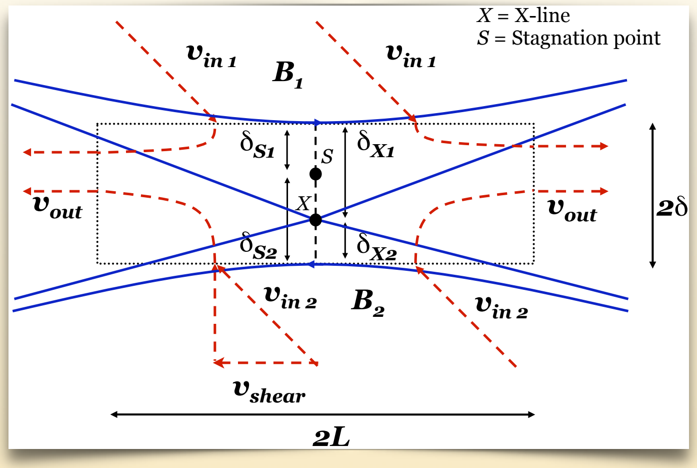
- Had been studied before, but mostly for symmetric reconnection (focus on component along reconnecting field)
  - Reconnection site (X-line) is stationary
  - Can lead to Kelvin-Helmholtz instability, especially at the flanks
  - Can suppress reconnection completely
    - Symmetric reconnection is suppressed if

$$v_{\rm shear}^2 > c_A^2$$

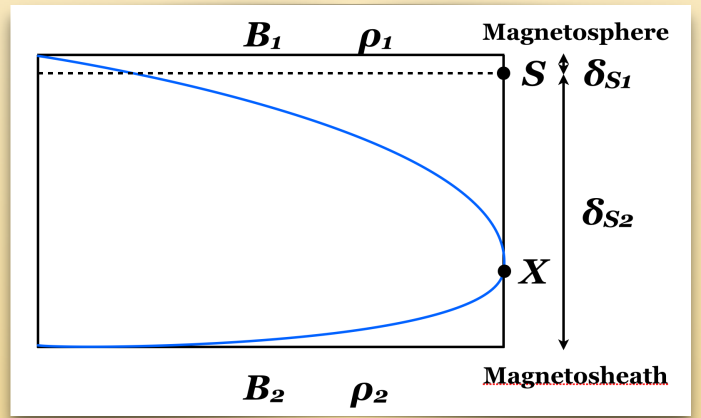
where $v_{shear} = (v_{sh,L} - v_{ms,L}) / 2$
  - When not suppressed, it slows reconnection (Cassak and Otto, 2011)

$$E_{\rm shear,sym} \sim E_0 \left(1 - \frac{v_{\rm shear}^2}{c_A^2}\right)$$

    - Not much work done on effect of flow on asymmetric reconnection (La Belle-Hamer et al., 1995; Tanaka et al., 2010)



- It turns out that asymmetries play an important role in how flow affects asymmetric reconnection (Doss et al., 2015)
  - The X-point and stagnation point are not in the center of the dissipation region (Cassak and Shay, 2007)
    - Related to balance of mass and energy flux
  - For typical magnetopause conditions, the large density asymmetry implies:
    - X-point is on magnetosheath side, stagnation point is far on magnetosphere side



Doss et al., 2015

This has important and unexpected effects on the reconnection process

Flow Makes Reconnection Site Move

- Asymmetries imply that X-line can drift even if flow is equal and opposite!
- In a steady-state, conservative form of momentum equation is

$$\oint d\mathbf{S} \cdot \left[\rho \mathbf{v}\mathbf{v} + \left(P + \frac{B^2}{8\pi} \right) \mathbf{I} - \frac{\mathbf{B}\mathbf{B}}{4\pi} \right] = 0$$

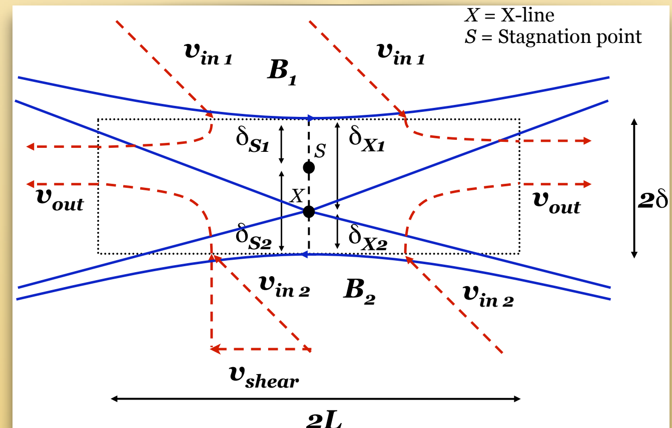
- Evaluate x-component (L in boundary normal coordinates) on all four sides:

$$2L_d \rho_1 [v_{in,1}(v_{L,1} - v_{\mathrm{drift}})] + 2L_d \rho_2 [v_{in,2}(v_{L,2} - v_{\mathrm{drift}})] \sim 0$$

- Solve for v_{drift}, using $v_{in,1}\ B_{L,1} \sim v_{in,2}\ B_{L,2}$:

$$\boxed{v_{\mathrm{drift}} \sim \frac{\rho_1 B_{L,2} v_{L,1} + \rho_2 B_{L,1} v_{L,2}}{\rho_1 B_{L,2} + \rho_2 B_{L,1}}}$$

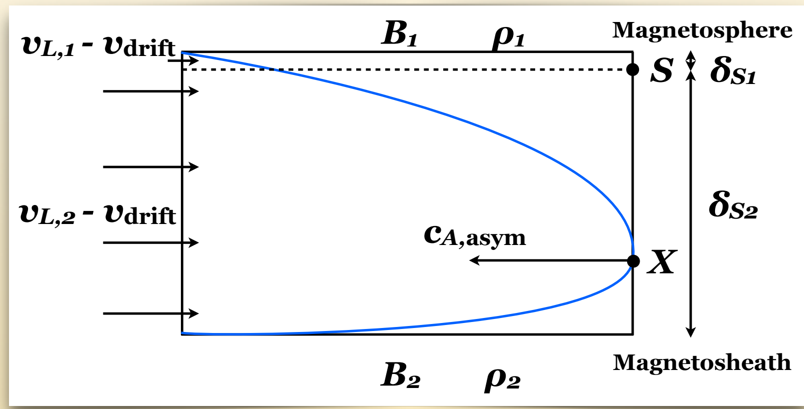
  - Note - assumes X-line is "isolated," *i.e.*, not influenced by other effects
    - The prediction does *not* mean all dayside reconnection sites should be flying downtail!



- What is the physics?
  - The upstream plasmas carry momentum in L direction
  - The side away from the stagnation point contributes more to the momentum of the dissipation region
    - Weighted in relation to its mass flux $\rho\ v_{in} \sim \rho / B_L$

The Reconnection Rate

- The reconnection rate is slowed by flow shear due to the momentum of the upstream plasma working against the tension of the reconnected field line
  - Analogous to suppression of reconnection by diamagnetic drift effects (Swisdak et al., 2003)



- For asymmetric reconnection, the outflow speed in the absence of flow shear (due to field line tension) is

$$c_{A,asym}^2 \sim \frac{B_{L,1}B_{L,2}}{4\pi}\frac{B_{L,1}+B_{L,2}}{\rho_1 B_{L,2}+\rho_2 B_{L,1}}$$

  - In asymmetric reconnection, the offset of the stagnation point means that upstream plasmas do not impede the flow equally; see the diagram. Therefore, we expect

$$v_{\rm out}^2 \sim c_{A,\rm asym}^2 - \frac{\delta_{S1}}{2\delta}(v_{L,1}-v_{\rm drift})^2 - \frac{\delta_{S2}}{2\delta}(v_{L,2}-v_{\rm drift})^2$$

- Using the expression for $v_{\rm drift}$ from before and some algebra gives

$$v_{\rm out}^2 \sim c_{A,\rm asym}^2 - (v_{L,1}-v_{L,2})^2\frac{\rho_1 B_{L,2}\rho_2 B_{L,1}}{(\rho_1 B_{L,2}+\rho_2 B_{L,1})^2}$$

- We expect the reconnection rate to generalize the symmetric result as

$$\boxed{E_{\rm shear,asym} \sim E_{\rm asym,0}\left(1-\frac{v_{\rm shear}^2}{c_{A,\rm asym}^2}\frac{4\rho_1 B_{L,2}\rho_2 B_{L,1}}{(\rho_1 B_{L,2}+\rho_2 B_{L,1})^2}\right)}$$

Condition for Suppression via Flow

- From the expression for the reconnection rate, the condition for suppression of reconnection by flow shear ($E_{shear,asym} \rightarrow 0$) is

$$\boxed{v_{\rm shear,crit} \sim c_{A,\rm asym} \frac{\rho_1 B_{L,2} + \rho_2 B_{L,1}}{2(\rho_1 B_{L,2} \rho_2 B_{L,1})^{1/2}}}$$

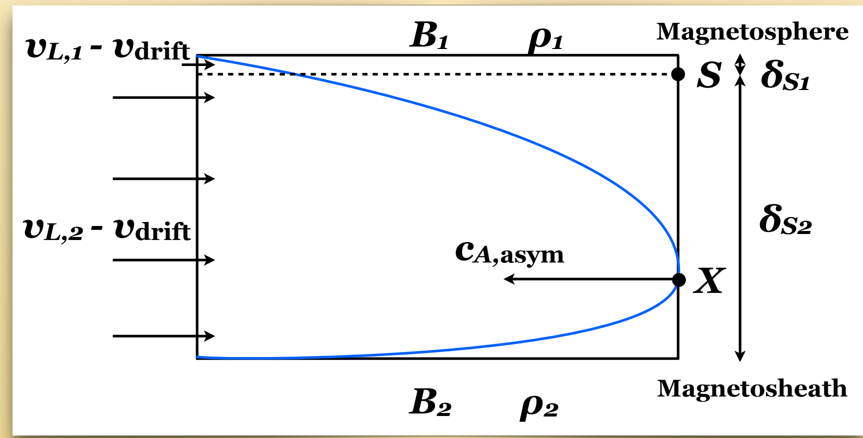
  - Related to the asymmetric outflow speed, but it is always larger!

- The physics (at Earth's magnetosphere)
  - The stagnation point is almost all the way to the magnetospheric side of dissipation region
  - The X-line moves essentially with the magnetosheath flow;
    - In the reference frame of the X-line, the magnetosheath is almost stationary, and the magnetosphere moves at the solar wind speed, but the density of the magnetosphere is so small that there is almost no effect!

- Consider magnetospheric parameters ($\rho_{ms} \gg \rho_{sh}$)
  - Critical speed for suppression is

$$v_{L,sh} > c_{A,\rm asym} \left(\frac{\rho_{sh} B_{ms}}{\rho_{ms} B_{sh}} \right)^{1/2}$$

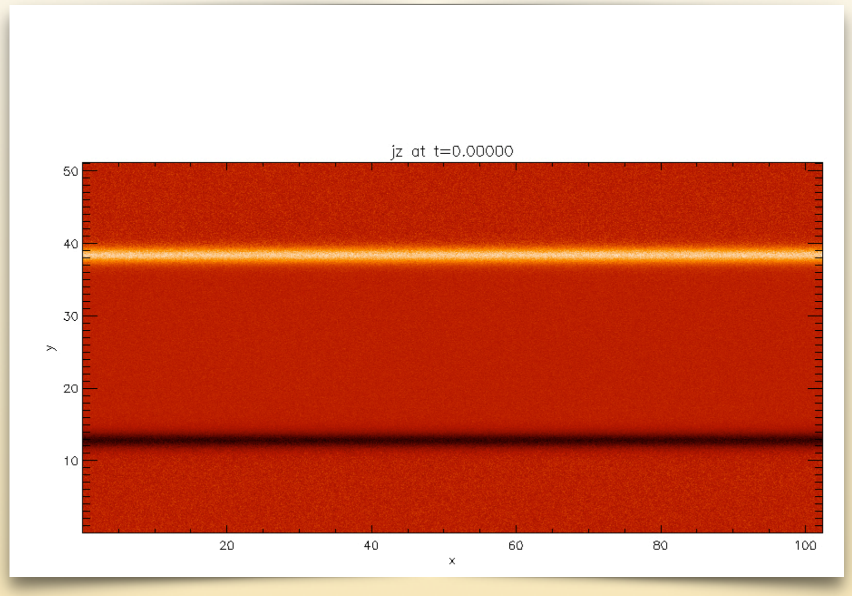
    - For event with B_{sh} ~10-15 nT, n_{sh} ~ 60-70 cm^{-3}, B_{ms} ~ 60 nT, n_{ms} ~ 0.5 cm^{-3} (Wilder et al., JGR, 2014), this implies critical magnetosheath flow of 22 x the asymmetric Alfven speed!!!



    - Much more difficult for flow shear to suppress asymmetric reconnection (of an isolated X-line) than thought!

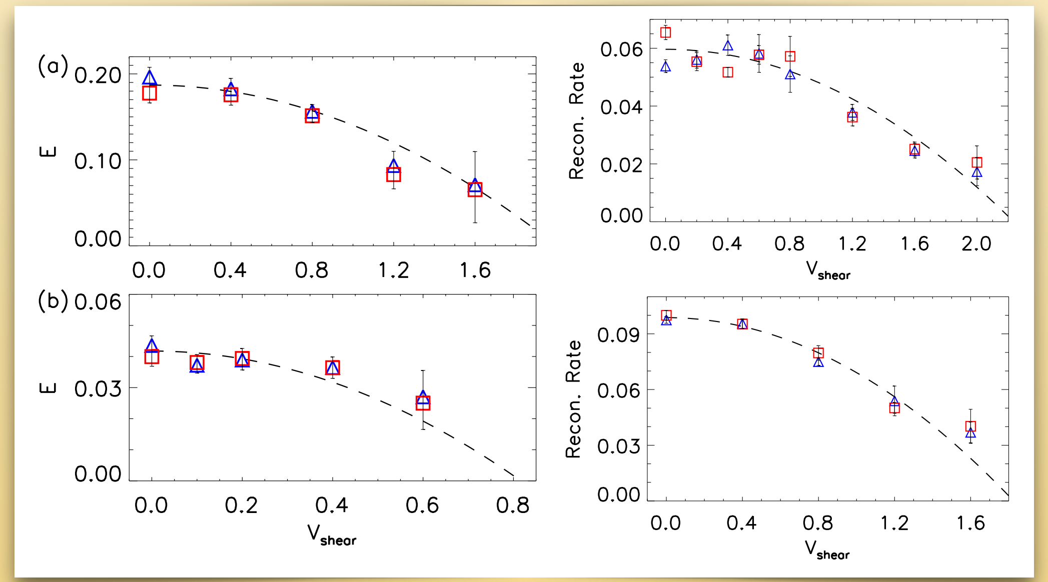
Testing Theory with Simulations

- We have tested the predictions in simulations with both two-fluid (Doss et al., JGR, 2015) and particle-in-cell (Doss et al., in prep.)
  - Two-fluid simulations with F3D (Shay et al., 2004)
    - Adiabatic ions, cold electrons
    - 2D, 204.8 x 102.4 d_i, grid 0.05, electron mass 1/25
    - Simulations with $B_{L,1} = 3$, $B_{L,2} = 1$ with symmetric density ($\rho = 1$) and $\rho_1 = 1$, $\rho_2 = 3$ for symmetric magnetic fields ($B_L = 1$), varying flow shear
  - PIC simulations with P3D (Zeiler et al., 2002)
    - 2D, electron mass 1/25
    - Simulations with $B_{L,1} = 1.5$, $B_{L,2} = 0.5$ with symmetric density ($\rho = 0.2$) with 204.8 x 102.4 d_i, grid 0.025, varying flow shear
    - Series of simulations with $\rho_1 = 0.6$, $\rho_2 = 0.2$ for symmetric magnetic field ($B_L = 1$) with 102.4 x 51.2 d_i, grid 0.05, varying flow shear



- Also did simulations with representative magnetopause conditions
  - PIC simulations with $B_{L,1} = 1.0$, $B_{L,2} = 2.0$, $\rho_1 = 1.0$, $\rho_2 = 0.1$, $v_1 = 1.0$ ("1" = sheath, "2" = sphere)
  - Movie shows out-of-plane current, middle is "magnetosphere," top/bottom are "magnetosheath"

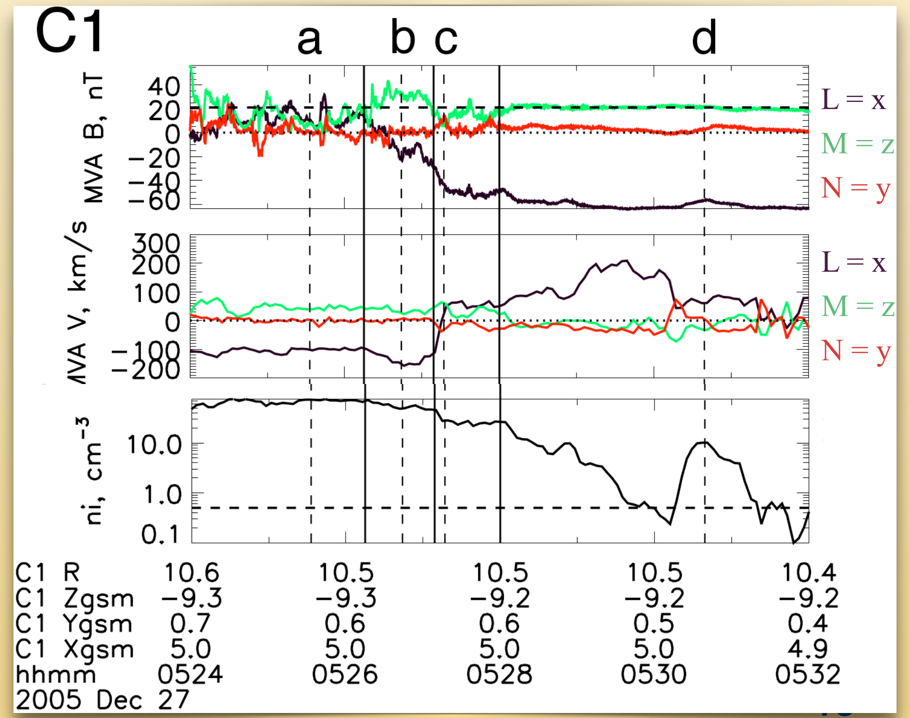
- Measured scaling of reconnection rate E with v_{shear}
  - Red boxes/blue triangles are data from two current sheets
    - Two-fluid: (top left) $B_1 = 3$, $B_2 = 1$, (bottom left) $\rho_1 = 1$, $\rho_2 = 3$
    - PIC: (top right) $B_1 = 1.5$, $B_2 = 0.5$, (bottom right) $\rho_1 = 0.6$, $\rho_2 = 0.2$
      - Dashed line is from prediction (using measured E_0)
      - Suppression condition consistent too!



Comparison to Cluster Observations

- Wilder et al., JGR (2014) observed an event near the cusp at the southern hemisphere with Cluster
  - C1 sees a reconnection event moving tailward, then C3 later sees the same event
    - From their separation and time delay, can determine how fast X-line is retreating
      - Estimate of convection speed is 105 km/s
    - L component of solar wind speed is 106 km/s

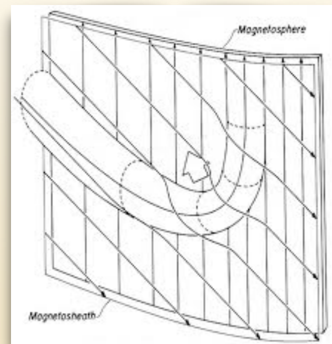
- Magnetosheath parameters are B_{sh} ~10-15 nT, n_{sh} ~ 60-70 cm^{-3}, magnetospheric parameters are B_{ms} ~ 60 nT, n_{ms} ~ 0.5 cm^{-3}
  - The theory predicts nearly identical v_{drift} and $v_{L,sh}$
    - Consistent with observations!
  - For these parameters, $c_{A,sh}$ ~ 28 km/s, v_{shear} ~ 53 km/s, $c_{A,asym}$ ~ 74.5 km/s
    - Reconnection would not happen in Cowley and Owen (1989) model
    - Certainly would in new model



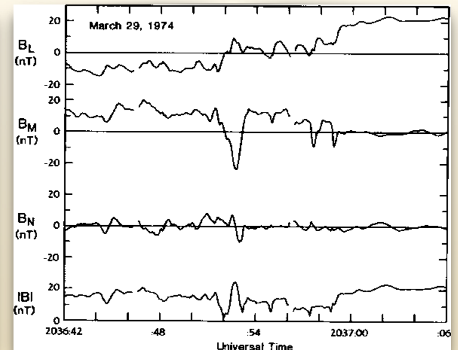
Wilder et al., 2014

Potential Application - FTE Motion

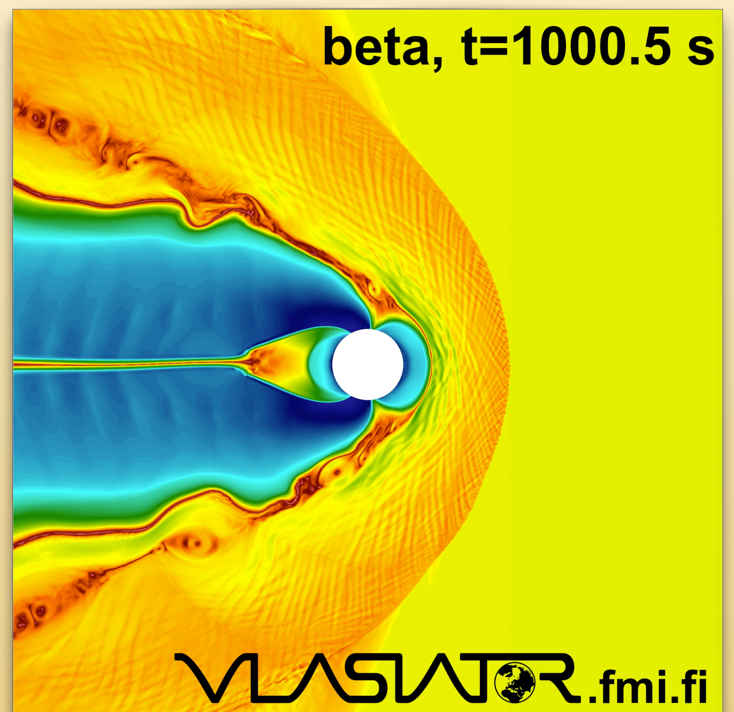
- FTEs are flux ropes/islands/plasmoids at the dayside magnetopause (Russell and Elphic, 1978)
  - Convect tailward; leading model is by Cowley and Owen, 1989
- Does new result impact understanding of FTE motion?
  - Seen in many simulations: global fluid (Berchem et al., 1995), hybrid (Omidi and Sibeck, 2007), in BATS-R-US simulations (Dorelli and Bhattacharjee, 2009)
  - New 2D Vlasov-fluid hybrid global magnetospheric code Vlasiator (Palmroth et al., 2012)
    - Copious production of FTEs
- How to address motion (following Omidi and Sibeck)
  - Locate center of FTEs
  - Track position as a function of time
  - Left plots: x and z position of FTEs as a function of time
    - Will be testing models (w/S. Hoilijoki)

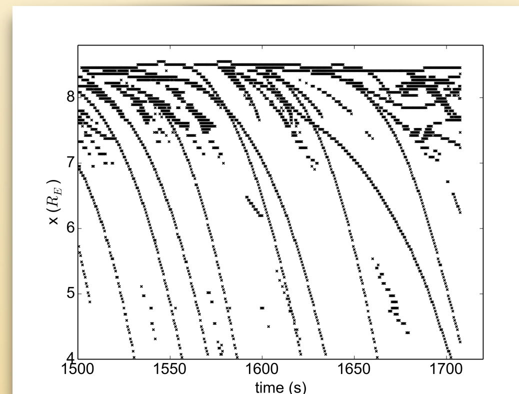


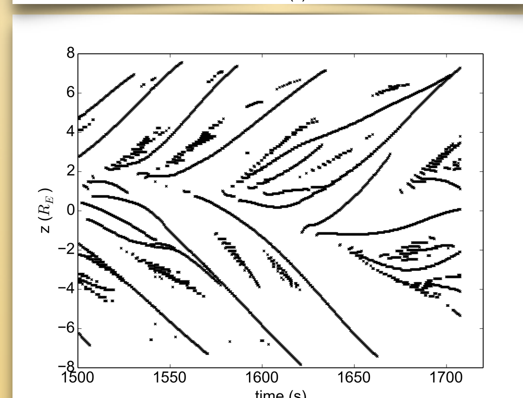
Russell and Elphic, 1978



Russell, 1990

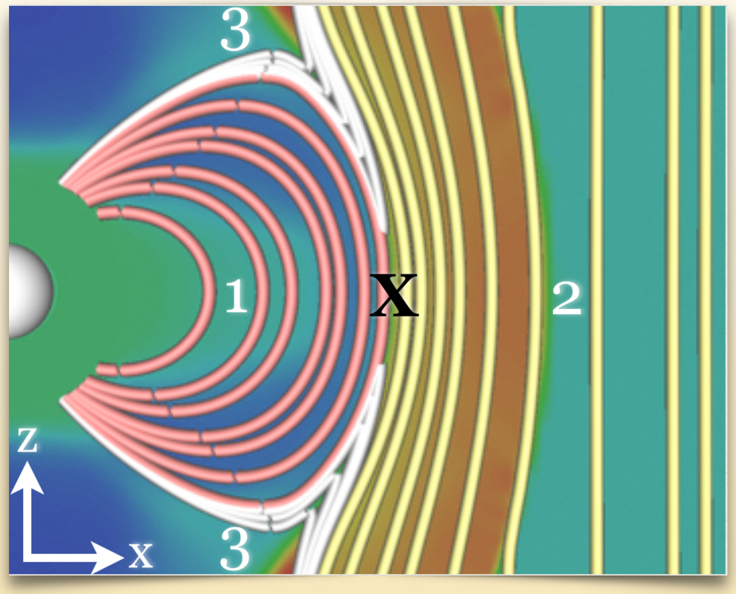






Does Local Picture Work in Global?

- (Eventual) goal - given conditions in solar wind, predict global and local reconnection rates
  - Modest first step - determine whether the (2D) predictions of local reconnection work in the (3D) magnetospheric geometry
    - Non-trivial! Has not been easy to even locate where dayside reconnection happens!
- For southward IMF (and no dipole tilt), finding reconnection is relatively easy
  - Magnetosheath and terrestrial magnetic fields are anti-parallel; reconnection happens in the ecliptic
    - Reconnection happens along a curve, not at a single point
  - Reconnection site is easy to pick out; it is where four topologies of magnetic field meet
    - Most previous studies use this geometry
- For oblique IMF, finding reconnection is very challenging!
  - No first principles way to predict its location, though maximum magnetic shear model (Trattner et al., 2007) and others get you close
    - How can 2D theory be tested if reconnection site can't even be located?!?
  - Good news - reconnection is still identifiable as location where four topologies meet
    - Called many things: "reconnection line", "separator"; we call it "X-line"
      - Note, separators are neither necessary nor sufficient to identify reconnection sites in general, but in magnetospheric geometry the concept works very well

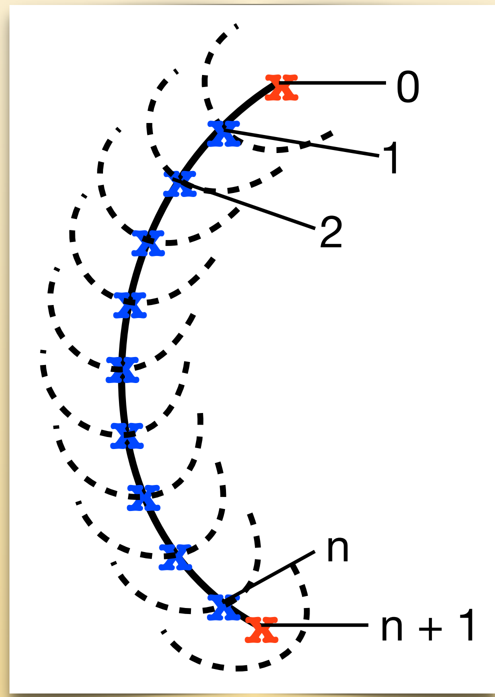


From C. M. Komar

Finding Reconnection Sites (X-lines)

- Solar context
  - Intersection of separator surfaces (Longcope and Cowley, 1996)
  - Progressive Interpolation Method (PIM) (Close et al., 2004)
  - Simulated annealing (Beveridge, 2006)

- Magnetospheric context
  - Map of field topology in a given plane (Dorelli and Bhattacharjee, 2009)
  - Sample topology, find where it changes along where separator (X-line) should be (Laitinen et al., 2006; 2007)
  - March from magnetic nulls with structure at rings (Haynes and Parnell, 2010)
  - Simple, robust method to find X-line (separators) (Komar et al., 2013)
    - Locate magnetic nulls (X) (Haynes and Parnell, 2007)
    - Center hemisphere at null, find topology of field lines on surface
    - Find point where topologies meet (X), center new hemisphere there
    - Repeat until other null is encountered
      - Works independent of IMF conditions, works to desired accuracy
  - Recent improvements (Glocer et al., 2016)
    - Extension of above to be more efficient and allow for bifurcating X-lines (FTEs)
    - Find intersection of separator surfaces
    - Find X-line location in collection of planes; more efficient than above mechanism

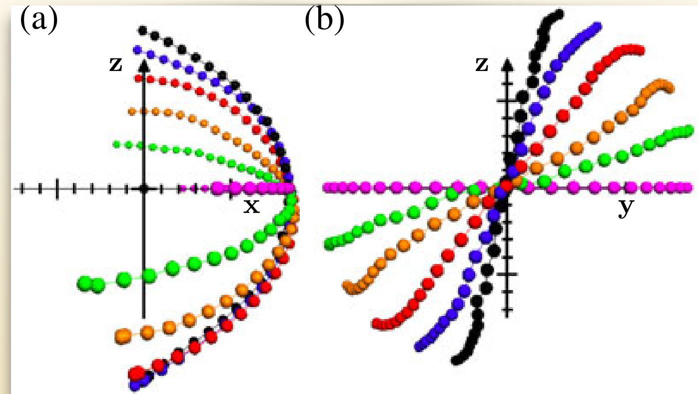


Komar et al., 2013

We used Komar et al. (2013) approach to find reconnection in many global MHD simulations

Local Properties of Reconnection

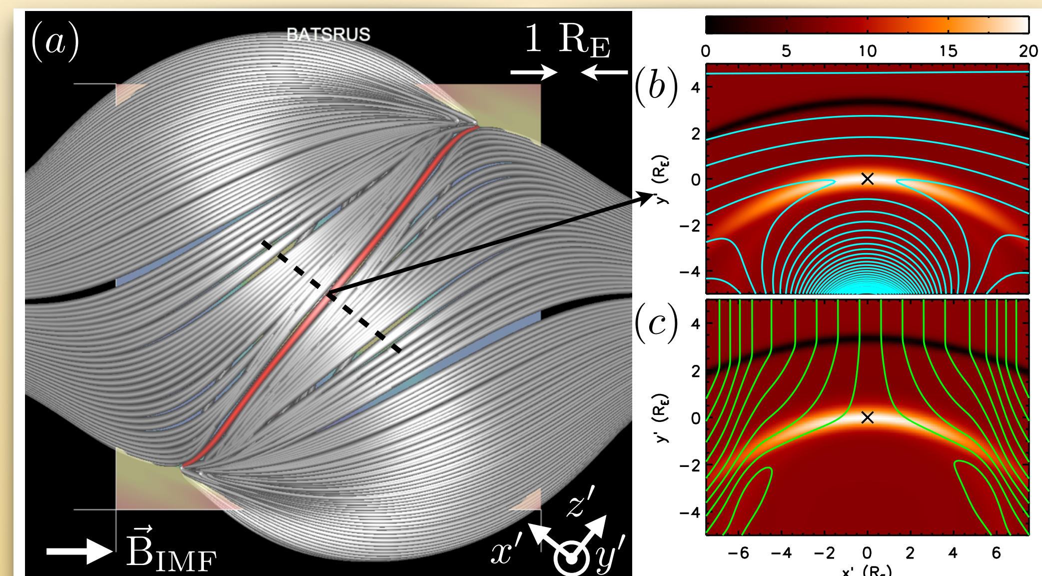
- Top plot - result of finding X-lines in simulations with different IMF clock angle (Komar et al., 2013)
  - Used BATS-R-US at NASA's CCMC (should work for any code though)
    - 3D resistive MHD, rectangular & irregular grid, highest resolution is 1/8 R_E
    - No dipole tilt with steady solar wind with no B_x (in GSM) for simplicity
    - Typical simulation - B_{IMF} = 20 nT, n_{SW} = 20 cm^{-3}, $v_{SW,x}$ = -400 km/s, T_{SW} = 20 eV (β_{SW} = 0.4)
    - Explicit resistivity $\eta/\mu_0 = 6.0 \times 10^{10}$ m^2/s



Komar et al., 2013

- Now we can test whether 2D models work in 3D (Komar and Cassak, submitted)
  - It is usually assumed that the plane of reconnection is normal to X-line
    - Not rigorous (Parnell et al., 2010)

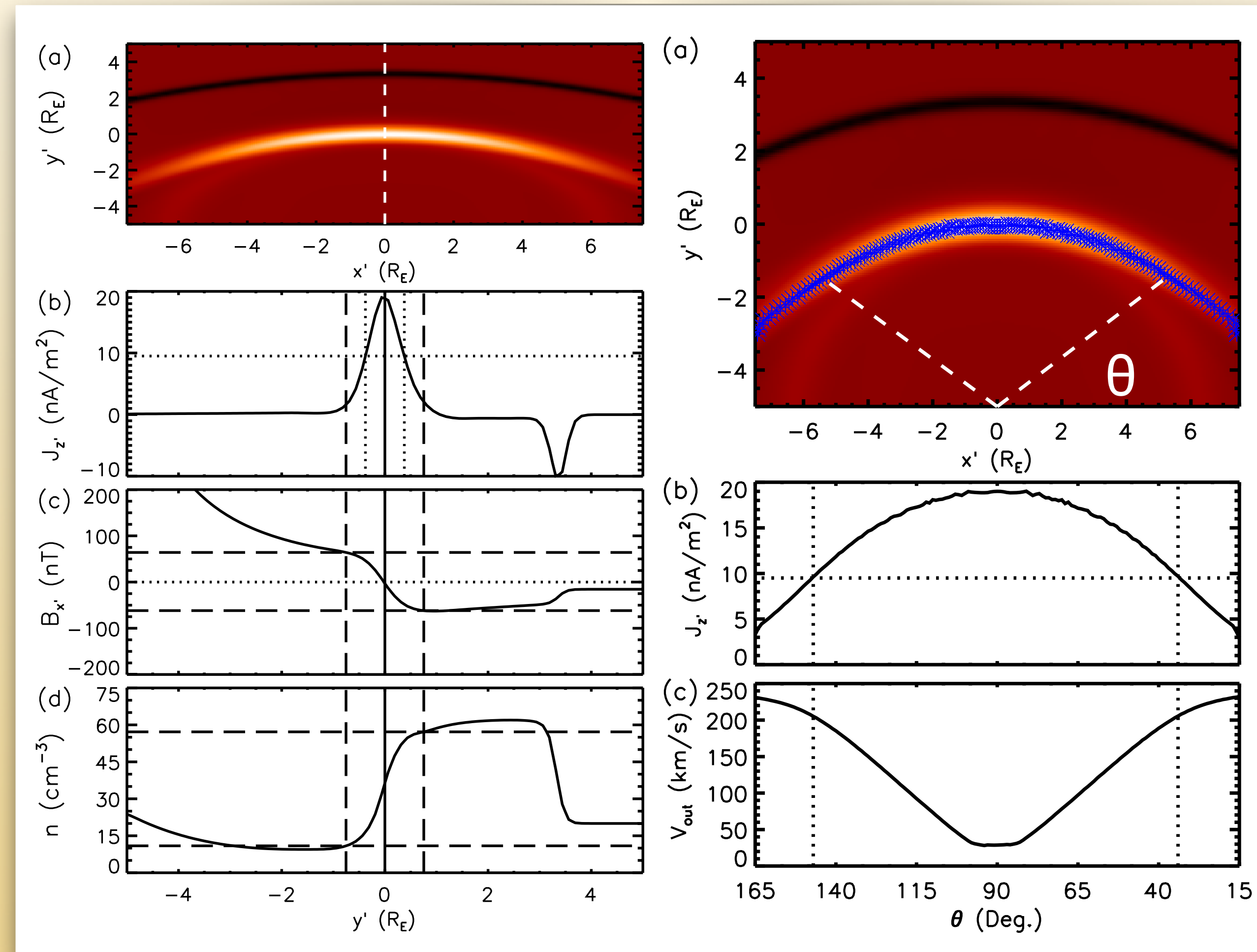
- Sample result (bottom left): $\theta_{IMF} = 90^o$
  - Reconnection plane through subsolar point
    - Lots of symmetry; generally symmetry is broken (asymmetric in *x'*; Murphy et al., 2010)
  - Plots show in-plane field lines in blue and in-plane flow lines in green
    - Qualitatively similar to 2D asymmetric reconnection



Komar and Cassak, submitted

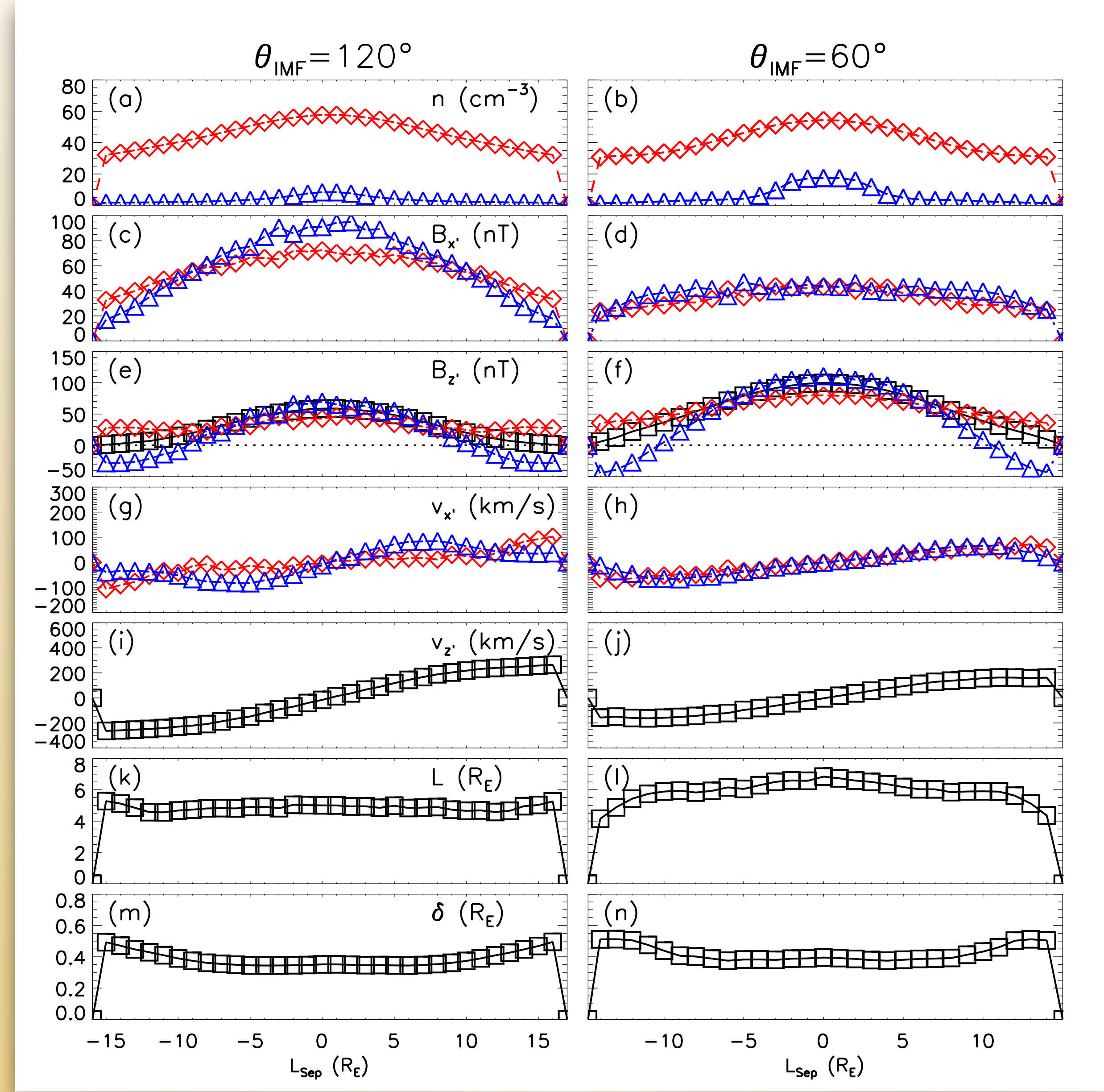
Towards Quantifying Local Reconnection

- To compare to 2D models of reconnection, we need to measure *local* plasma parameters in reconnection planes (all of them!) (Komar and Cassak, submitted)
  - Inflow direction (left plot):
    - HWHM of $J_{z'}$ in y' direction is thickness δ
      - 0.76 R_E here
    - Measure plasma parameters 2δ upstream from peak in current
      - $B_{SH,x'} = -61$ nT, $n_{SH} = 57\ cm^{-3}$ $B_{MS,x'} = 64$ nT $n_{MS} = 11\ cm^{-3}$
  - Outflow direction (right plot):
    - In cuts, find max of $J_{z'}$ as a function of θ
    - HWHM of $J_{z'}$ along sheet is length L
      - 5.84 R_E
    - Find v_{out} at same location



Komar and Cassak, submitted

Upstream Parameters Along X-line



Quantifying Dayside Reconnection

- Can test local reconnection models (Komar and Cassak, submitted)
  - Test simplest asymmetric reconnection model (Cassak and Shay, 2007)

$$E \sim \frac{B_{MS,x'} B_{SH,x'}}{B_{MS,x'} + B_{SH,x'}} c_{A,out} \frac{2\delta}{L}$$

$$E \sim \sqrt{\frac{\eta c_{A,out}}{\mu_0 L} B_{MS,x'} B_{SH,x'}}$$

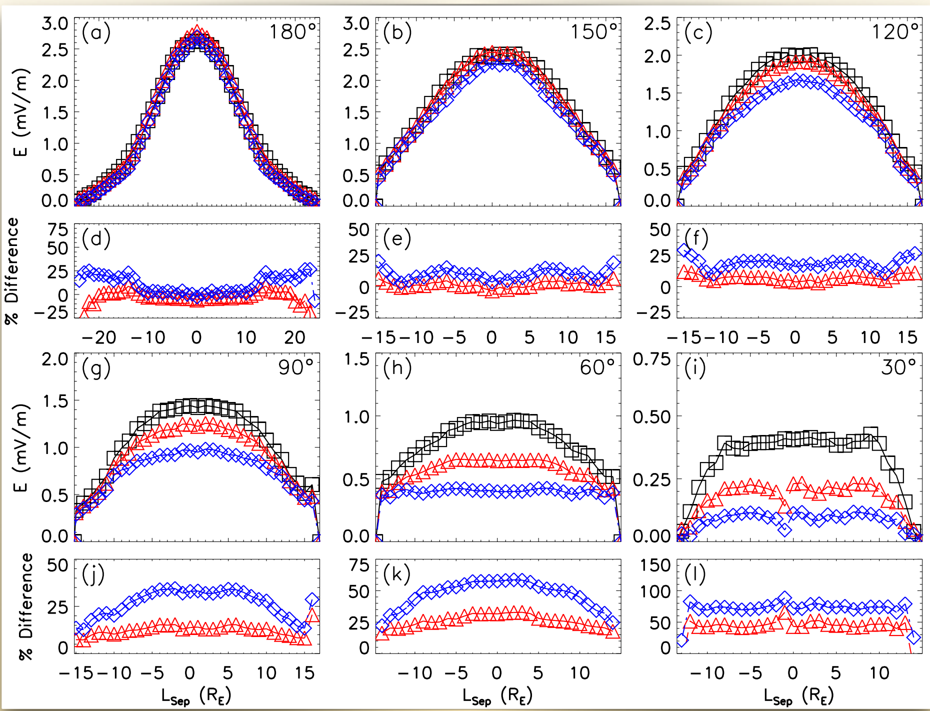
$$c_{A,out}^2 \sim \frac{B_{MS,x'} B_{SH,x'}}{\mu_0} \frac{B_{MS,x'} + B_{SH,x'}}{\rho_{SH} B_{MS,x'} + \rho_{MS} B_{SH,x'}}$$

- Previous tests:
  - Global simulations - worked with/without plumes in BATS-R-US (Borovsky et al., 2008), agreement “reasonable” with LFM (Ouellette et al., 2014)
    - All of these studies were for special case of essentially due-southward IMF
  - Observations - best fit of data from Polar (Mozer and Hull, 2010), recent study of multiple events (Wang et al., 2015)

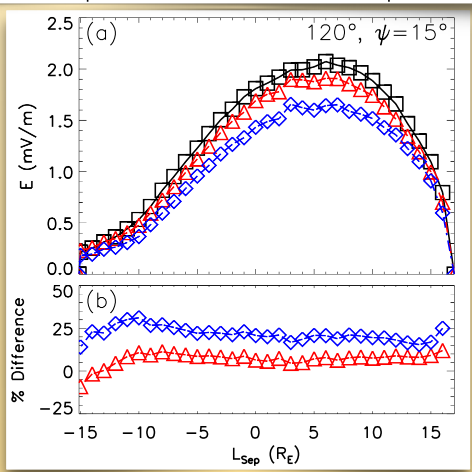
- Model limitations
  - Does 2D model work in 3D magnetosphere?!?
  - Theory has no guide field, no magnetosheath flow
  - Theory ignores asymmetry in outflow direction (Murphy et al., 2010)

Results

- Test for various clock angles, Black - measured *E*, blue - general prediction, red - resistive prediction
  - Agreement for $\theta_{IMF} = 180^{\circ}$ is excellent!
    - Agrees with Borovsky et al., 2008; Ouellette et al., 2014
  - Agreement in absolute sense becomes worse for lower clock angles
  - % difference relatively flat in subsolar region; implies agreement in scaling sense



- Test of robustness: check results in system where all symmetries are broken
  - $\theta_{IMF} = 120^{\circ}$ with a dipole tilt of 15° (northern hemisphere tilted towards sun)
  - Similar scaling agreement to no dipole tilt case



- Conclusion of this study *so far* (Komar and Cassak, submitted):
  - With only few assumptions, comparison between global resistive-MHD simulations and a small set of overly simplistic 2D prediction shows:
    - Exceptional agreement for due southward IMF
    - Very good agreement in a scaling sense for oblique IMF (including northward IMF!)
      - Northward IMF cases very interesting; reconnection rate is peaked near subsolar point! (Glocer et al., 2016)
  - A systematic effect leads to poorer agreement in the absolute sense for oblique IMF

Summary and Discussion

- First principles prediction of solar wind-magnetospheric coupling requires an understanding of local and global properties of dayside reconnection

- Local
  - We have a prediction for the convection speed of isolated X-lines and the reconnection rate for asymmetric reconnection with arbitrary upstream parallel flows (Doss et al., 2015)
    - Assumptions: “isolated” current sheet (no line tying), 2D, anti-parallel reconnection, no asymmetries in outflow direction, no flow in out-of-plane direction, used fluid theory
  - Significant departures from standard expectations
    - Effect on reconnection rate is minimal for typical magnetopause parameters; requires solar wind speed <u>much</u> bigger than Alfvén speed to suppress reconnection
    - May have something to say about tailward motion of FTEs (Cowley and Owen model)

- Global
  - 2D predictions agree very well in a scaling sense for oblique IMF (for systems we tested) (Komar and Cassak, submitted)

- Discussion and future directions
  - Local
    - Need to include out-of-plane (guide) magnetic fields
      - Non-trivial - introduces diamagnetic drifts (Swisdak et al., 2003; Phan et al., 2013)
        - » Only know of one study - Tanaka et al., 2010
    - Asymmetric outflow (Murphy et al., 2010; Oka et al., 2011)
    - Flow in the out-of-plane direction (only a few)
    - Manifestly 3D effects?
  - Global
    - How does local picture of reconnection fit in to global considerations?